Theory of Double Beta Decay: Nuclear-Physics Aspects

Jouni Suhonen

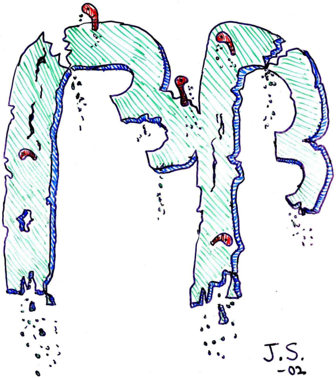
Department of Physics, University of Jyväskylä

Prospects of Neutrino Physics
Tokyo, Japan, April 8 - 12, 2019

Contents:

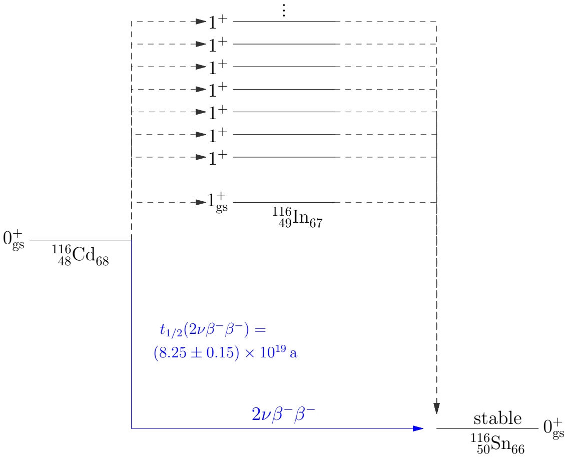
- Intro: DBD rates
- Effective value of g_A
- Impact on $0\nu\beta\beta$ NMEs
- OMC: a new way to test $0\nu\beta\beta$ NMEs
- Spectral shapes and reactor-$\bar{\nu}$ spectra

INTRO: Rates of double beta decay

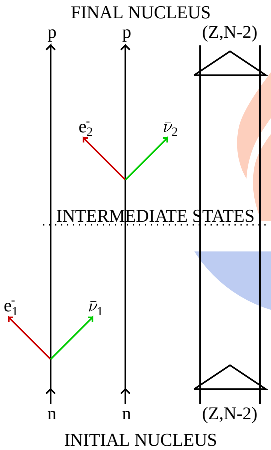


See the recent review: H. Ejiri, J. Suhonen, K. Zuber, Neutrino-nuclear responses for astro-neutrinos, single beta decays and double beta decays, Physics Reports 797 (2019) 1–102

Two-Neutrino Double Beta Decay of ^{116}Cd

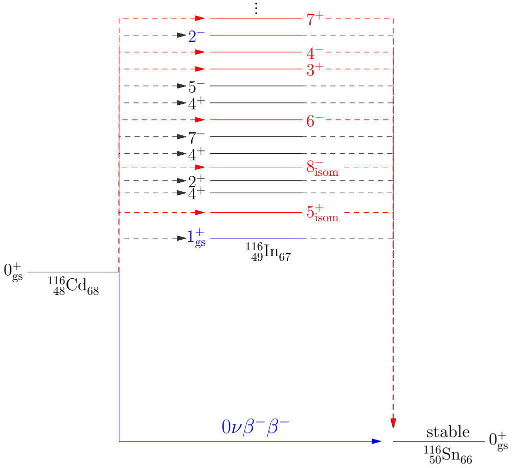


$t_{1/2}(2\nu\beta^-\beta^-) =$
$(8.25 \pm 0.15) \times 10^{19}$ a

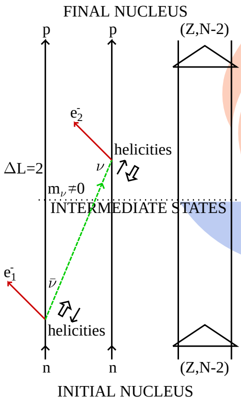


$$2\nu\beta\beta - \text{rate} \sim \left|M^{(2\nu)}_{\rm GTGT}\right|^2 = (g_{\rm A})^4 \left|\sum_{m,n} \frac{M_{\rm L}(1^+_m)M_{\rm R}(1^+_n)}{D_m}\right|^2$$

Neutrinoless Double Beta Decay of ^{116}Cd



MASS MODE



$$\boxed{0\nu\beta\beta-\text{rate} \sim \left|M^{(0\nu)}_{\rm GTGT}\right|^2 = (g_{\rm A,0\nu})^4 \left|\sum_{J^\pi} (0^+_f||\mathcal{O}^{(0\nu)}_{\rm GTGT}(J^\pi)||0^+_i)\right|^2}$$

Studies of the effective values of the weak couplings ($g_{\mathrm{V}}, g_{\mathrm{A}}, g_{\mathrm{P}}$)

Motivation:

Effective values of weak couplings are involved in all weak processes, and thus have impact on

- studies of rare β decays
- processes in neutrino physics ($\beta\beta$ decay, low-energy (anti)neutrino-nucleus scattering, nuclear muon capture, . . .)
- processes in astrophysics (allowed and forbidden β decays, (anti)neutrino-nucleus scattering cross sections,. . .)

Sources of quenching or enhancement of g_A

The free-nucleon value of g_A is changed in nuclear-structure calculations by:

- Non-nucleonic degrees of freedom (e.g. Δ resonances)
- Effects beyond the impulse approximation (e.g. two-body meson-exchange currents)
- Deficiencies in nuclear many-body approaches (e.g. restricted valence spaces, lacking many-body configurations, omission of three-body nuclear forces)

Definitions

See also: "Value of the axial-vector coupling strength in β and $\beta\beta$ decays: A review" published in **Frontiers in Physics 5 (2017) 55**.

Nucleon weak current in a nucleus:

$$j_{\mathrm{N}}^{\mu} = g_{\mathrm{V}}\gamma^{\mu} - g_{\mathrm{A}}\gamma^{\mu}\gamma^{5}$$

Quenching:

$$q = g_{\mathrm{A}}/g_{\mathrm{A}}^{\mathrm{free}}$$

Free value of g_{A} (Particle Data Group 2016) from the decay of free neutron:

$$g_{\mathrm{A}}^{\mathrm{free}} = 1.2723(23)$$

Effective value of g_{A}:

$$g_{\mathrm{A}}^{\mathrm{eff}} = q g_{\mathrm{A}}^{\mathrm{free}}$$

Gamow-Teller β and $2\nu\beta\beta$ decays

There are data on:

Gamow-Teller β transitions and $2\nu\beta\beta$ transitions

For these we have the low-momentum-exchange limit

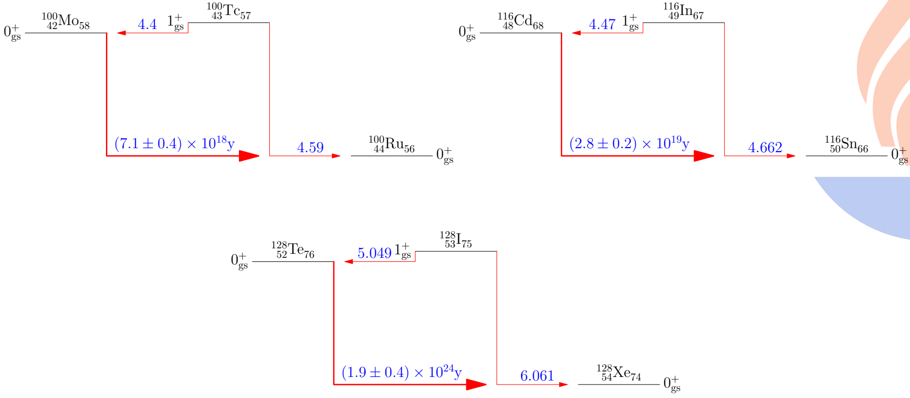
$$g_{\mathrm{A},0\nu}(J^\pi) \xrightarrow{q\to 0} g_{\mathrm{A}}(J^\pi),$$

where the usual convention is $g_{\mathrm{A}} \equiv g_{\mathrm{A}}(1^+)$

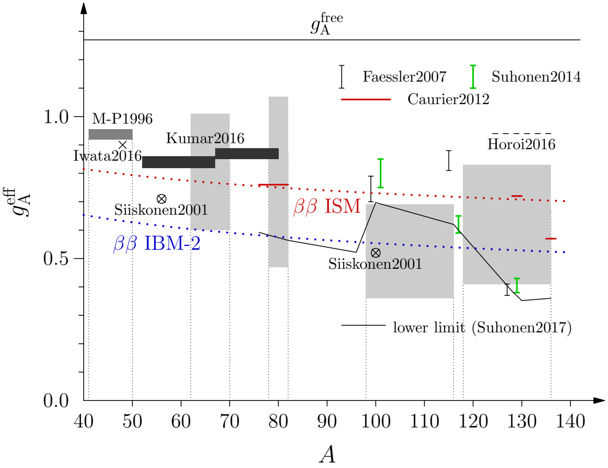
Nuclear models:

ISM (Interacting Shell Model)
pnQRPA (proton-neutron QRPA)
IBM-2 (microscopic interacting boson model)

Typical Gamow-Teller β and $2\nu\beta\beta$ transitions



Results extracted from the GT β+$2\nu\beta\beta$ calculations



- Faessler2007: pnQRPA A. Faessler *et al.*, arXiv 0711.3996v1 [Nucl-th]
- Suhonen2014: pnQRPA J. Suhonen *et al.*, Nucl. Phys. A 924 (2014) 1
- Suhonen2017: pnQRPA J. Suhonen, Phys. Rev. C 96 (2017) 055501
- Caurier2012: ISM E. Caurier *et al.*, Phys. Lett. B 711 (2012) 62
- Horoi2016: ISM M. Horoi *et al.*, Phys. Rev. C 93 (2016) 024308
- M-P1996: ISM G. Martínez-Pinedo *et al.*, Phys. Rev. C 53 (1996) R2602
- Iwata2016: ISM Y. Iwata *et al.*, Phys. Rev. Lett. 116 (2016) 112502
- Kumar2016: ISM V. Kumar *et al.*, J. Phys. G 43 (2016) 105104 Phys. Lett. B 711 (2012) 62
- Siiskonen2001: ISM T. Siiskonen *et al.*, Phys. Rev. C 63 (2001) 055501
- $\beta\beta$ ISM and IBM-2: J. Barea *et al.*, Phys. Rev. C 87 (2013) 014315
- Light hatched regions: pnQRPA H. Ejiri *et al.*, J. Phys. G 42 (2015) 055201 ; P. Pirinen *et al.*, Phys. Rev. C 91 (2015) 054309 ; F. Deppisch *et al.*, Phys. Rev. C 94 (2016) 055501

Forbidden β decays and the value of g_{A}

Results from:

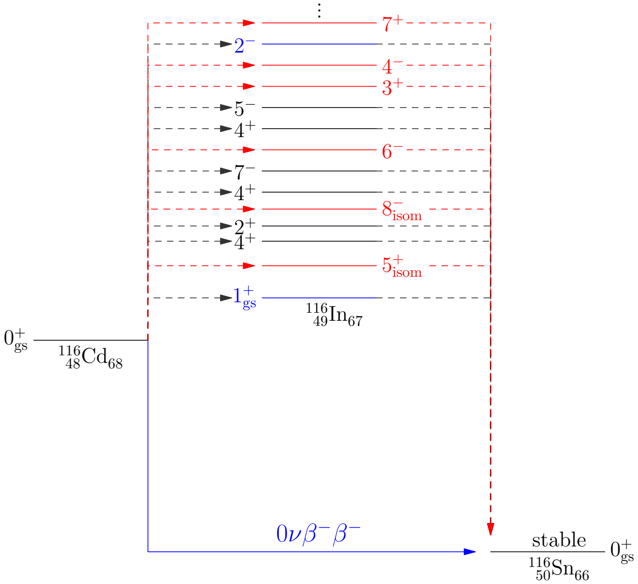
Quenching of $g_{\mathrm{A}}(J^{\pi})$

as derived from

β decays

of forbiddenness K

INCENTIVE: $0\nu\beta\beta$ decay through the higher angular-momentum states



Novel approach: Spectrum-shape method (SSM)

Results for higher-multipole transitions:

Effective value of $g_{\mathrm{A}}(J^{\pi})$

as derived from

electron spectra of

forbidden non-unique β decays

Spectrum shape of higher-forbidden non-unique β decays

Half-life:

$$t_{1/2} = \kappa/\tilde{C}\,.$$

Dimensionless integrated shape function:

$$\tilde{C} = \int_1^{w_0} C(w_e)\, p w_\mathrm{e} (w_0 - w_e)^2 F_0(Z_f, w_e)\, \mathrm{d}w_e\,.$$

Shape factor:

$$C(w_e) = \sum_{k_e,k_\nu,K} \lambda_{k_e}\left[M_K(k_e,k_\nu)^2 + m_K(k_e,k_\nu)^2 - \frac{2\gamma_{k_e}}{k_e w_e} M_K(k_e,k_\nu)\, m_K(k_e,k_\nu)\right]\,,$$

where

$$\lambda_{k_e} = \frac{F_{k_e-1}(Z,w_e)}{F_0(Z,w_e)}\,;\quad \gamma_{k_e} = \sqrt{k_e^2-(\alpha Z_f)^2}\,,$$

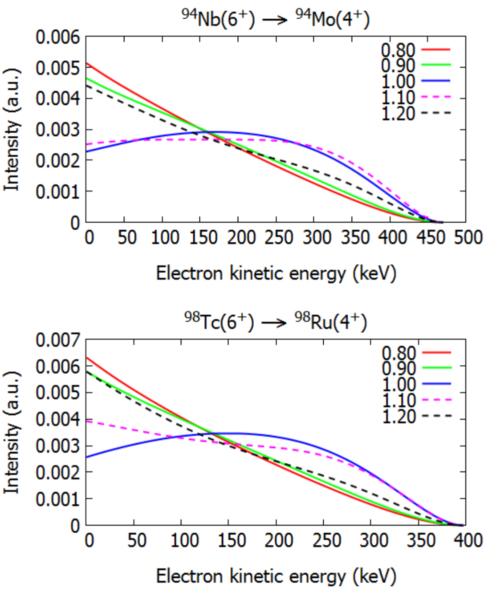
$F_{k-1}(Z,w_e)$ being the generalized Fermi function.

Decomposition of the shape factor:

$$\boxed{C(w_e) = g_\mathrm{V}^2 C_\mathrm{V}(w_e) + {g_\mathrm{A}}^2 C_\mathrm{A}(w_e) + g_\mathrm{V} g_\mathrm{A} C_\mathrm{VA}(w_e).}$$

ISM-computed β spectra for different values of g_A

Normalized ISM-computed electron spectra for the $2nd$-forbidden nonunique β^- decays of ^{94}Nb and ^{98}Tc ($g_V = 1.0$).

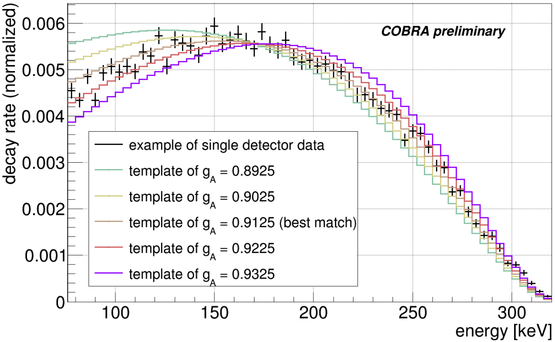


Example: Decay of ^{113}Cd – Comparison with data

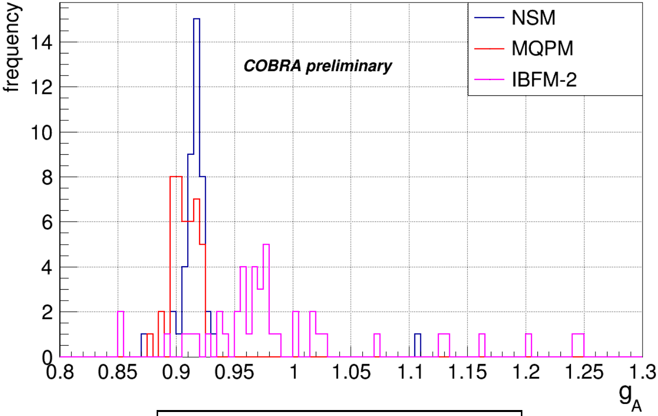
Normalized electron spectra for the $4th$-forbidden nonunique β^- decay $^{113}\mathrm{Cd}(1/2^+) \rightarrow {}^{113}\mathrm{In}(9/2^+)$ $(g_\mathrm{V} = 1.0)$.

Experimental data from:

The COBRA collaboration, L. Bodenstein-Dresler *et al.*, arXiv:1806.02254 [nucl-ex] 6 Jun 2018



Distribution of the best-match g_A values from 44 detector units



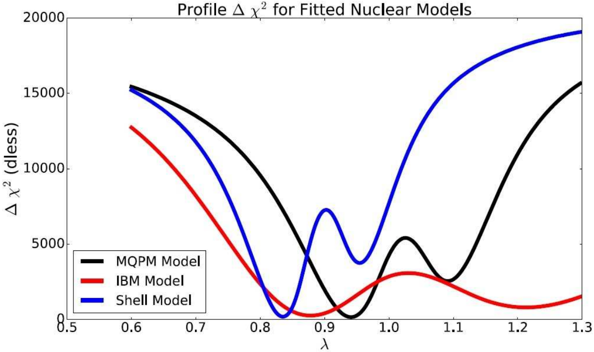
$$\bar{g}_A(\mathrm{ISM}) = 0.92 \pm 0.02$$
$$\bar{g}_A(\mathrm{MQPM}) = 0.91 \pm 0.01$$
$$\bar{g}_A(\text{IBFM-2}) = 0.94 \pm 0.09$$

Example: Decay of ^{115}In – Comparison with data

Normalized electron spectra for the $4th$-forbidden nonunique β^- decay $^{115}\mathrm{In}(9/2^+) \rightarrow {}^{115}\mathrm{Sn}(1/2^+)$ ($g_\mathrm{V} = 1.0$).

Result from:

The MIT-CSNSM-Jyväskylä collaboration, A. Leder *et al.*, to be submitted.



$$\bar{g}_\mathrm{A}(\mathrm{ISM}) = 0.83 \pm 0.03$$
$$\bar{g}_\mathrm{A}(\mathrm{IBFM\text{-}2}) = 0.88 \pm 0.06$$
$$\bar{g}_\mathrm{A}(\mathrm{MQPM}) = 0.94^{+0.03}_{-0.04}$$

Effects of quenched values of g_A

Results from:

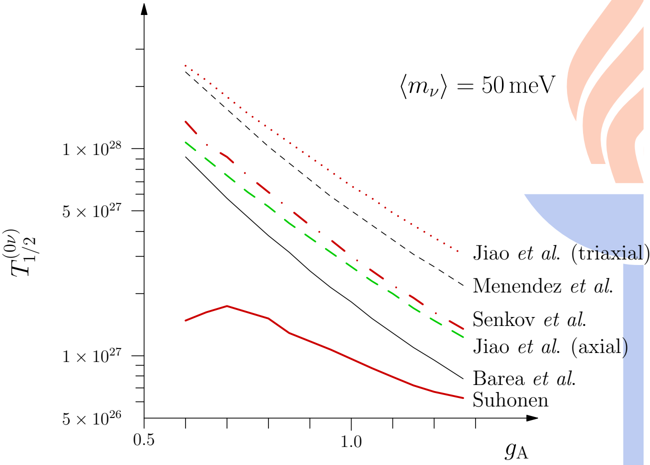
Effects of a quenched g_A on NMEs of $0\nu\beta\beta$ decays:

$$\boxed{\left[T_{1/2}^{(0\nu)}\right]^{-1} = (g_{\mathrm{A},0\nu})^4 G^{(0\nu)} \left|M^{(0\nu)}\right|^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2}$$

$$\boxed{M^{(0\nu)} = M_{\mathrm{GT}}^{(0\nu)} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A},0\nu}}\right)^2 M_{\mathrm{F}}^{(0\nu)} + M_{\mathrm{T}}^{(0\nu)}}$$

Example: $0\nu\beta\beta$ NMEs of ^{76}Ge, effect on the half-life

- Jiao *et al.*: Phys. Rev. C 96 (2017) 054310 (GCM+ISM)
- Menendez *et al.*: Nucl. Phys. A 818 (2009) 139 (ISM)
- Senkov *et al.*: Phys. Rev. C 93 (2016) 044334 (ISM)
- Barea *et al.*: Phys. Rev. C 91 (2015) 034304 (IBM-2)
- Suhonen: Phys. Rev. C 96 (2017) 055501 (pnQRPA + isospin restoration + data on $2\nu\beta\beta$)



OMC as a probe of $0\nu\beta\beta$ NMEs

There are and will be more data on:

CAPTURE RATES

OF

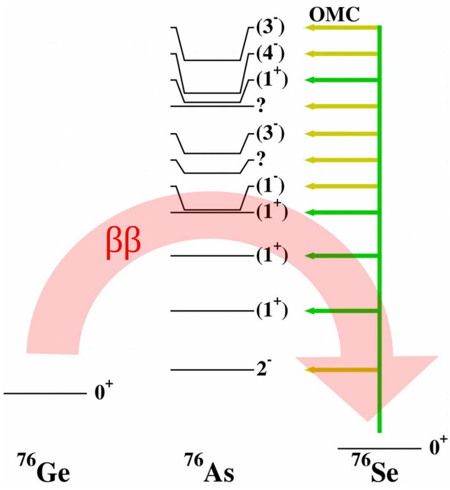
ORDINARY MUON CAPTURE (OMC)

In particular:

OMC STRENGTH FUNCTIONS

Ordinary Muon Capture on ^{76}Se

$$^{76}\mathrm{Se} + \mu^- \rightarrow {}^{76}\mathrm{As} + \nu_\mu$$



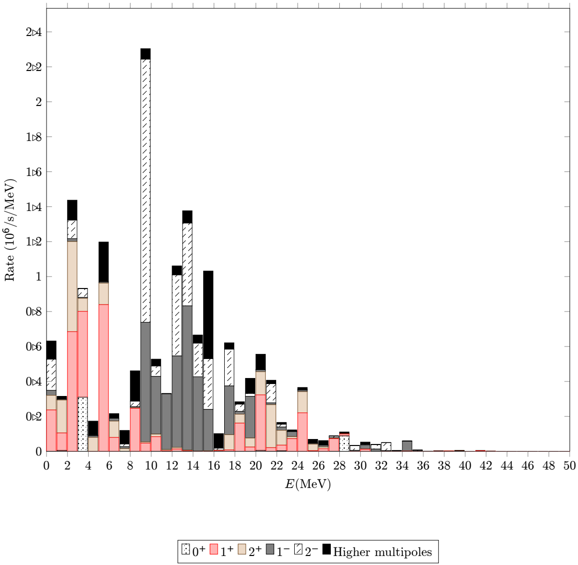
$$\boxed{m_\mu c^2 \approx 105\,\mathrm{MeV}}$$

- OMC and $0\nu\beta\beta$ operate in the $q \approx 100\,\mathrm{MeV}$ momentum-exchange region $\Rightarrow g_{\mathrm{A},0\nu}(J^\pi)$
- Induced currents (g_P!) are activated

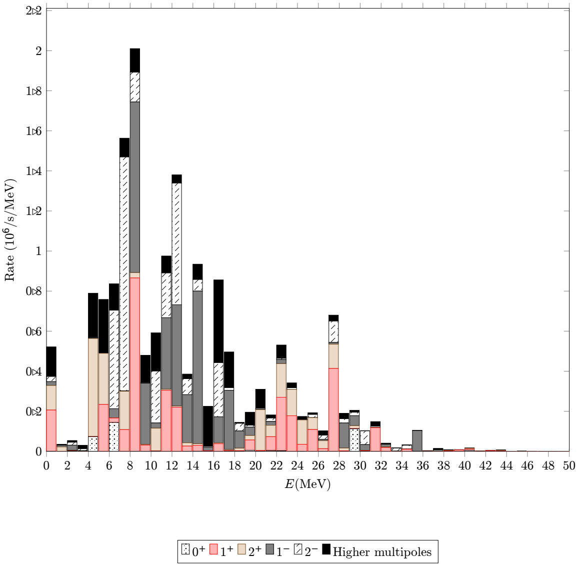
Experiments:

RCNP, Osaka and J-PARC MLF, Japan

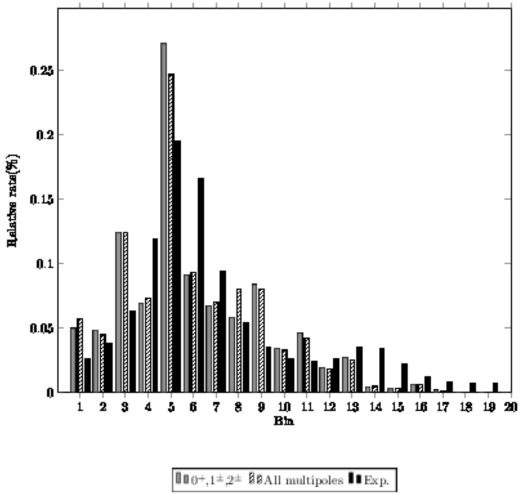
OMC strength function on ^{76}Ge



OMC strength function on ^{100}Ru



Comparison of experimental and computed OMC rates on ^{100}Mo



Experiments: MuSIC beam channel at RCNP (Research Center for Nuclear Physics), Osaka, Japan

D2 beam channel in J-PARC (Japan Proton Accelerator Research Complex) MLF, Ibaraki, Japan

Novel application of electron spectra of forbidden decays

Try to investigate:

Reactor-$\bar{\nu}$ anomaly

and

the spectral shoulder

Neutrino-related anomalies imply oscillations to sterile neutrinos

Sterile neutrinos:

The gallium anomaly

The reactor antineutrino anomaly

imply oscillations of the "ordinary" neutrinos (ν_e, ν_μ, ν_τ) to

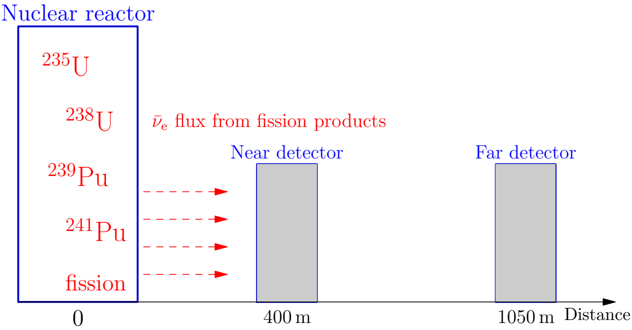
STERILE NEUTRINO

in the mass range of a few eV

But what is the reactor antineutrino anomaly?

The reactor antineutrino anomaly

The $\bar{\nu}_e$ flux from reactors has been measured in short-baseline neutrino-oscillation experiments[1]: Daya Bay (in Daya Bay, China; 6 reactors, 8 detectors), RENO (South Korea; 2 detectors 294m and 1383 m from 6 reactors) and Double Chooz (Chooz, France, 2 detectors 400m and 1050 m from 2 reactors, schematic figure below).



---

[1] RENO: Phys. Rev. Lett. 108 (2012) 191802; Double Chooz: J. High Energy Phys. 2014 (2014) 86; Daya Bay: Phys. Rev. Lett. 116 (2016) 061801.

The neutrino-flux measurements find:

The reactor $\bar{\nu}_{\mathrm{e}}$ anomaly:

The measured flux is some 5% smaller than that predicted from the β decays of the fission yields of the reactor fuel

$\overset{?}{\Longrightarrow}$ Oscillations to STERILE NEUTRINOS

The bump anomaly:

There is an unexpected bump at $4 - 6$ MeV (spectral shoulder) in the measured $\bar{\nu}_{\mathrm{e}}$ spectrum.

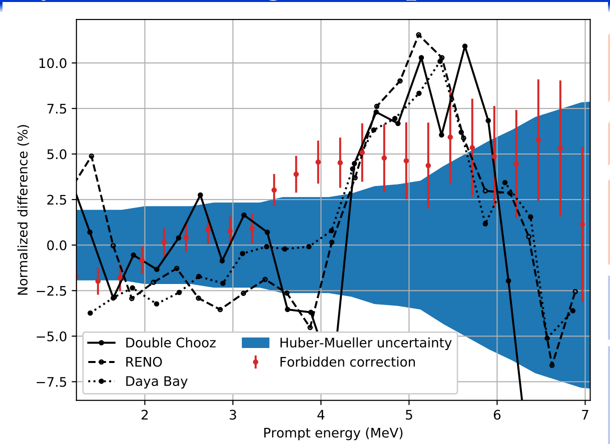
$\Longrightarrow$???

Results from the analyses including the β spectra

Taking into account the (first-forbidden) decays of

^{86}Br(0^+), ^{86}Br(2^+), ^{87}Se, ^{88}Rb, ^{89}Br($3/2^+$), ^{89}Br($5/2^+$), ^{90}Rb, ^{91}Kr($5/2^-$), ^{91}Kr($3/2^-$), ^{92}Rb, ^{92}Y, ^{93}Rb, ^{94}Y(0^+), ^{94}Y(0^+), ^{95}Rb($7/2^+$), ^{95}Rb($3/2^+$), ^{95}Sr, ^{96}Y, ^{97}Y, ^{98}Y, ^{133}Sn, ^{134m}Sb(6^+), ^{134m}Sb(6^+?), ^{135}Te, ^{136m}I, ^{137}I, ^{138}I, ^{139}Xe, ^{140}Cs, ^{142}Cs

decreases the $\bar{\nu}$ flux by some 5% !



The spectral sholder appears due to forbidden spectral corrections !

See: L. Hayen, J. Kostensalo, N. Severijns, J.Suhonen, First-forbidden transitions in reactor antineutrino spectra, Phys. Rev. C 99 (2019) 031301(R)

Conclusions and Outlook

Conclusions:

- The effective value of g_A is involved in all weak processes, and thus has impact on studies of rare β decays, neutrino physics and astrophysics
- The long chain of ISM calculations and the recent pnQRPA and IBM-2 calculations of Gamow-Teller β decays and $2\nu\beta\beta$ decays are (surprisingly!) consistent with each other and clearly point to a A-dependent quenched g_A
- The spectrum-shape method (SSM) for forbidden non-unique β decays is a robust tool (largely independent of the nuclear model, the assumed Hamiltonian and mean field) to seach for the effective value of g_A and to try to solve other problems, like those related to the reactor-$\bar{\nu}$ spectra: Proper account of the spectral shapes of first-forbidden β decays is instrumental in the quest for the solution to the anomaly.
- The OMC can test the weak axial couplings at the momentum-exchange region relevant for the $0\nu\beta\beta$ decay

Outlook:

- Urge measurements of the β spectra for the interesting decays amenable to the SSM
- Measurements of the OMC rates for the $0\nu\beta\beta$-decay daughters will yield important information on the (induced) axial couplings relevant for $0\nu\beta\beta$ decay

The end

THANKS FOR PATIENCE!